

**DEPARTMENT OF THE ARMY  
U.S. Army Corps of Engineers  
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CECW-EE

Technical Letter  
No. 1110-2-550

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**Engineering and Design  
RELIABILITY ANALYSIS OF HYDROPOWER EQUIPMENT**

**1. Purpose**

This engineer technical letter (ETL) provides basic guidance for assessing the reliability of hydropower equipment and establishes an engineering basis for rehabilitation investment decisions. The methodology, concepts, and background information are briefly stated with further explanation and examples in the appendices. This letter also references the hydropower benefits analysis and the economic models as they relate to hydropower rehabilitation projects.

**2. Applicability**

This ETL applies to all HQUSACE elements and USACE commands having responsibilities for civil works hydroelectric power plant projects.

**3. References**

Required and related publications are listed in Appendix A.

**4. Background**

Reliability analyses are a required and significant part of the economic justification for funding of rehabilitation and major maintenance projects.

*a.* In FY 1992, major rehabilitation projects began being budgeted under Construction, General, and Flood Control, Mississippi River and Tributaries, appropriation accounts. Total implementation costs of hydropower rehabilitation projects must be in excess of \$5.3 million for FY 1998 submittals, and the work must extend over two full construction seasons to qualify under the major rehabilitation program. The cost threshold amounts are adjusted annually for inflation as published in the Annual Program and Budget Request for Civil Works Activities, Corps of Engineers, EC 11-2-172. Proposals for these projects are subjected to a much more rigorous economic analysis than in the past. Not only is it necessary to show that the monetary benefits of major rehabilitation work exceed the cost, but it must also be demonstrated that each component in a rehabilitation plan is incrementally justified and that the combination of components proposed yields the maximum net benefits. In short, proposals for major rehabilitation work must be supported by the same level of economic analysis as that for new water resource development projects. The Chapter 3 of the ER 1130-2-500 establishes the policy for major rehabilitation at completed Corps projects. The Chapter 3 of the EP 1130-2-500 established guidance for the preparation and submission of Major Rehabilitation Projects Evaluation Reports for annual program and budget submissions. They should be consulted for the most recent policy on types of improvements that can be pursued under the Major Rehabilitation program

and the basic assumptions for the economic analysis. Currently, reliability is the key factor in determining whether there is a Federal interest in a proposed replacement. If an equipment replacement is reliability-driven, the investment is generally Federally funded. An increase in output which is primarily incidental to the reliability work may also be included in such a project. However, non-Federal funding is required to fund the project if there are no reliability problems and the proposed project purpose is only to improve output beyond the original design. Contact CECW-B for current policy on non-Federal funding of generation improvements.

*b.* Hydropower major maintenance work items also require reliability analysis and economic justification. Major maintenance includes projects, such as a generator rewind, with total estimated costs that exceed \$3 million and do not qualify as Major Rehabilitation. Specific guidance on hydropower major maintenance evaluation requirements is being drafted by CECW-B.

## 5. Reliability Concepts

There are some basic reliability concepts which arise from statistics and are utilized in evaluating reliability. The definitions of the terms used to represent these concepts and the definitions of terms more specific to hydropower equipment reliability analyses follow.

*a. Risk.* The exposure to a chance of loss or injury; the likelihood of adverse consequences. Expressions of risk are composed of the following two parts:

- (1) The existence of unwanted consequences.
- (2) The occurrence of each consequence expressed in the form of a probability.

*b. Certainty.* A condition where determinacy exists in the elements that characterize a situation. The likelihood of an event occurring and its consequences are known absolutely.

*c. Uncertainty.* A condition where indeterminacy exists in some of the elements that characterize a situation. Uncertainty may exist from either probability uncertainty or outcome uncertainty or any of the pathways between the initiating event and the consequences.

*d. Variability.* The existence of differences in the numerical quantities within the same population. Uncertainty and variability have some of the same connotations. With variability, the range of possible values is usually known, perhaps along with other information such as the distribution. However, uncertainty allows the values for a quantity to retain an element of vagueness that is not characterized in quantities exhibiting variability. This suggests that if placed on a continuum from complete randomness to complete determinacy, variability is somewhere closer to certainty than uncertainty is.

*e. Reliability of power plants.* There are risks associated with the possible failure of operating power plants. The risks include repair costs and higher power generating costs. A generating unit that has been derated because of previous problems is not capable of producing the same amount of power that it could originally produce. That is a certainty. The exact amount of power the unit can produce in the derated condition is uncertain. The probability that a generating unit will fail after it has been on line for 20 years has variability. The engineering reliability analysis required for a major maintenance rehabilitation proposal needs to consider these reliability concepts.

*f. Equipment reliability.* Hydropower equipment reliability is defined as follows: The extent to which the generating equipment can be counted on to perform as originally intended. This encompasses the confidence in soundness or integrity of the equipment based on forced outage experience and maintenance costs, the output of the equipment in terms of measured efficiency and capacity, unit availability, and the dependability of the equipment in terms of remaining service life (retirement of the equipment).

## 6. Engineering Reliability Analysis

This section discusses the many facets of reliability of hydropower equipment in relatively broad terms. Appendices B through E go into further detail by exploring a theoretical project and applying an analysis to that project. The overall engineering reliability analysis consists of four independent analyses to determine the following equipment reliability factors: (a) forced outage experience and maintenance costs; (b) efficiency and capacity; (c) availability; and (d) dependability. The life-cycle costs of each segment are compiled for use in the economic analysis. Benefits for each alternative are calculated by subtracting the average annual equivalent life-cycle costs for the alternative from the average annual equivalent life-cycle costs for the base condition. The following paragraphs briefly summarize each segment of the reliability analysis.

*a. Forced outage experience and maintenance costs.* A forced outage occurs when a power plant component fails to perform satisfactorily and causes an interruption in power production. A planned outage occurs when a unit is intentionally taken out of service to perform planned repairs, replacements, routine inspections, and rehabilitations.

(1) The life-cycle cost of equipment maintenance and repair includes labor and material costs as well as lost energy and capacity benefits associated with forced or planned outages. Therefore, reliability is a determining factor in estimating life-cycle costs. Decreased reliability may be represented by a large increase in labor and materials costs over time. Certainly, increasing maintenance costs and unit outage hours can both be used to indicate a need for equipment replacement or rehabilitation. Project records for the equipment in question can be used to document past trends and as a basis to make future projections. Currently, such documentation may be the only justification required for replacing relatively low cost items that are critical for power production. In the near future, economic justification that incorporates reliability will be required. The economic justification will be conducted using the Hydropower QUADRANT model, HYD-QUAD. CECW-B should be

contacted on the requirements for justifying relatively low cost items below the main rehabilitation and major maintenance thresholds and for using HYD-QUAD. HYD-QUAD is discussed in Appendix F.

(2) Caution must be exercised when relying on maintenance costs as indicators of reliability because they do not necessarily reflect equipment reliability. Explanations of costs and maintenance efforts should be presented in the evaluation reports. Maintenance and repair records should be tabulated and charted to show the trends over the past few years. Projections for future years can be made using sound engineering judgment to extrapolate these costs and should be made for each of the alternatives being considered. Lost energy and capacity are discussed below under the topic of availability.

*b. Efficiency and capacity.* This portion of the reliability analysis can be applied to any piece of equipment that has an effect on the ability of the generating unit to produce rated power at rated efficiency. However, this approach is primarily applicable to the turbines, generators, and transformers. Turbines will be used as an example in the following explanation.

(1) Part of the aging process of turbines is the development of cracks, corrosion, erosion, scaling, and cavitation damage. Much of this damage is corrected by welding, which induces material stresses and can change the shape of the turbine water passage thereby lowering the efficiency of the turbine. Thus, degradation of turbine performance occurs as a result of the aging process and can be exacerbated by repairs which are necessary to keep the turbine operational.

(2) The first step in quantifying the performance degradation is to determine current and original levels of performance. Current efficiency and power output must be determined by field testing at similar settings used in the original field tests. The current performance must then be compared with the original level of performance to establish the amount of performance degradation that has occurred. Original levels of performance

can be established from model tests and acceptance test data. It is important to fully investigate the calibrations and calculations of the data in order to truly compare the original and current performance.

(3) The information derived from this testing and analysis is provided as input to the hydroelectric power benefits analysis, which is discussed in Appendix D. The benefits analysis estimates the power system production costs using a full range of unit availability which can be applied to the base case and each alternative.

*c. Availability.* Availability is the annual percentage of time that the generating equipment is available for power production. Records of availability are maintained by each project on a unit-by-unit basis. The current level of availability must be compared with previous data to establish the extent of degradation. Historical trends can be extrapolated to project future changes in the unit availability rate. Availability data are also used as input to the hydroelectric power benefits analysis.

*d. Dependability (reliability).*

(1) The final area of consideration concerning equipment reliability is dependability. Dependability is ascertained by a risk analysis that determines the probability that the equipment will not perform satisfactorily in any given year. The output from this risk analysis is used in the probabilistic life-cycle cost analysis. One way to graphically represent the probabilistic life-cycle cost model is with event trees. A discussion of event tree models is presented in Appendix E. Two methods of probabilistic risk analysis are frequently used. The first method uses historical data and an evaluation of the condition of the equipment to determine a statistical distribution of age at retirement. This method is characterized by the use of reliability curves. The second method is similar to that used in structural evaluations. It extends the safety factor concept by using a probabilistic approach to determine a reliability index. The method that is most appropriate depends upon the type of equipment being evaluated and the specific situation.

(2) Hydropower equipment is typically operated until it fails or is retired for some other reason. Failure meaning that it ceases to function properly under the stresses applied. Replacement and refurbishment are both considered as constituting the effective retirement of a piece of equipment. The first major reason for equipment retirement is physical condition, which includes deterioration with time, wear from use, and failure in service. The second reason for retirement is related to functional situations, which include inadequacy to perform required functions, potential for improvement (uprating), and obsolescence. These may occur due to a change in environment, operating conditions, or load requirements. The first category, physical condition, is the primary reason that the Corps developed the Major Rehabilitation Program. This program establishes a standardized method of considering and evaluating the deterioration and wear of equipment in an effort to optimize rehabilitation actions. Failures in service are generally not evaluated under the Major Maintenance and Rehabilitation Programs, but are funded through reprogramming Operation and Maintenance funds. Reliability is the key factor in determining whether there is a Federal interest in a proposed replacement. As previously stated, if there are no reliability problems and the proposed project purpose is to solely improve output beyond the original design (improvement in functional situations), non-Federal funding is required to fund the project. It also may happen that a replacement is reliability-driven, Federally funded, and there is increased output which is primarily incidental to the reliability work.

## 7. Risk Analysis Using Reliability Curves

Historically, engineering judgment has been used to predict remaining unit life and determine the probability that the unit will perform unsatisfactorily. The Corps has embarked on a program to attempt to structure these predictions and determinations. Methods of determining reliability are well established for many types of physical properties. A useful way of expressing reliability for the Corps' economic evaluations is the annual

probability that a piece of equipment will fail to perform satisfactorily. The following discussions explain the terms and their applications used in this process.

a. The following two functions are used in the development of reliability curves.

(1) The reliability of equipment can be considered a continuous variable with a probability density function (pdf) of  $f$ . A pdf is a theoretical model for the frequency distribution of a population of measurements. In this case regarding reliability, the pdf is the rate of change of the equipment dependability. Therefore, if the dependability of the equipment at age  $a$  is defined as:

$$D(a) = P(A > a)$$

where

$A$  = age of the equipment at retirement

and

$P(A > a)$  = probability that  $A > a$  (Ayyub, Kaminskiy, and Moser 1996)

Then the pdf of  $D(a)$  is

$$f(a) = \frac{dD(a)}{da} = D(a)$$

This simply states that the dependability of a piece of equipment is equal to the probability that the equipment is still functioning at age  $a$ .

(2) The hazard function  $H(a)$ , or incremental failure rate associated with the random variable  $A$ , is given by:

$$H(a) = \frac{d \ln D(a)}{da} = -\frac{D'(a)}{D(a)}$$

That is, the incremental failure rate is equal to the probability of the equipment life being age  $a$  divided by the probability of the equipment

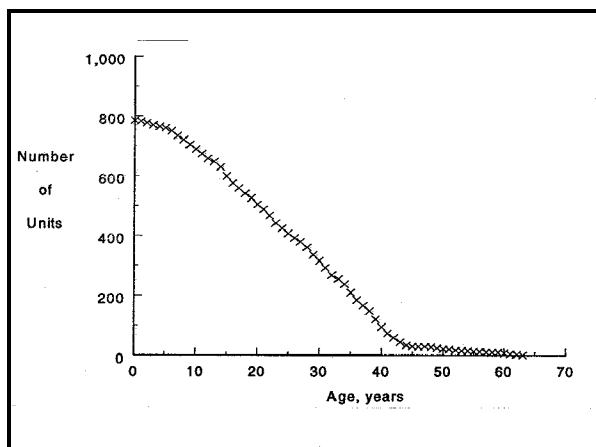
surviving to age  $a$  in the first place. It is the probability that the failure occurs at age  $a$ .

b. The Corps is continuing to assemble a large database of equipment histories to establish the reliability characteristics of various categories of equipment. The initial work in this area focused on generator stator windings because there have been a significant number of stator retirements in the form of rewinds (Ayyub, Kaminskiy, and Moser 1996), but a significant turbine database is also being developed. The historical data include many attributes such as year installed, age at failure, and rated capacity. Appendix F presents a review of recent research in hydropower reliability analysis. The raw data are compiled and reduced into annual summaries of exposures and failures.

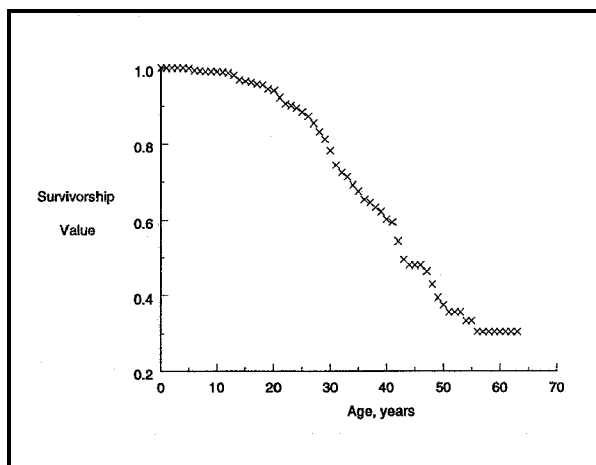
c. The raw retirement data can be fitted using any number of means. One method is the application of Iowa Curves developed in the 1930's by the Engineering Experiment Station at what was then Iowa State College (Winfrey 1935). Other distribution functions that may be used include normal, exponential, log-normal, and Weibull. The Weibull distribution is one of the most widely used reliability functions. It has been shown that the differences between the Iowa Curves and a Weibull distribution are statistically insignificant. The Weibull distribution is much easier to adapt to computer analysis techniques. Research to develop new and more refined reliability functions continues.

d. The practice in Corps evaluation reports has been to use the hazard function directly if the condition of the specific equipment in question is considered average. If, however, the equipment has exhibited signs of premature or accelerated deterioration, the hazard function has been adjusted to account for the evident higher probability of failure. Similarly, the hazard function can be modified to account for lower failure probabilities for equipment that is in better condition than average. Contact the Hydroelectric Design Center (HDC) for the current details on modifying hazard functions.

e. Figure 1 is a plot of generator raw data showing the number of units performing satisfactorily given years in service or age. Figure 2 shows these data plotted as a reliability curve, with percent in service as the ordinate. Figures 3 and 4 then show these data fitted to a Weibull curve and the resultant hazard function, respectively.

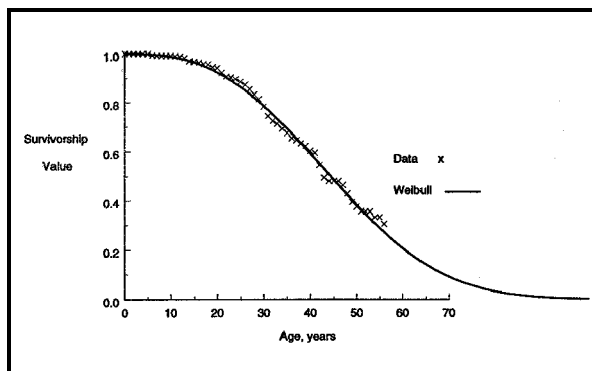


**Figure 1. Generator stator windings. Number of units performing satisfactorily versus years in service**

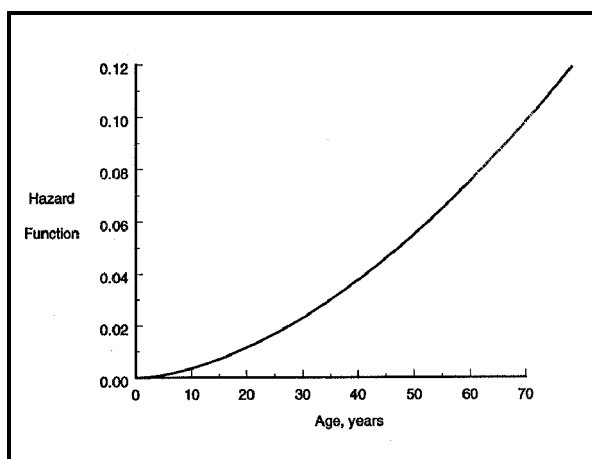


**Figure 2. Generator stator windings. Reliability curve**

f. The factor being used by the Corps to evaluate equipment condition and modify the frequency curve data is the condition indicator (CI). Condition indicator evaluation methods have been developed by the Corps for many types of equipment and structures (USACE 1993). CI's are



**Figure 3. Generator stator windings. Weibull distribution**



**Figure 4. Generator stator windings. Hazard function from Weibull distribution**

a screening tool which provides a uniform method of evaluating condition through testing and inspections. Inspection and test data are gathered and condition index numbers assigned for each unit in accordance with the latest guidance. Equipment with CI values from 70 to 100 is considered to be in very good to excellent condition. CI values in this range, when applied to the survivor curve, will tend to show increased reliability. Equipment with CI values in the midrange, from 40 to 69, is considered fair to good. The best prediction of this equipment's reliability is the statistical baseline data of similar equipment. Therefore, there is no cause to adjust the baseline frequency curve for equipment that falls into this category. Equipment with a CI below 40 is considered to be in poor condition or worse. CI values below 40 will tend to

increase the probability of failure and the baseline frequency curve is adjusted. It is important to note that the methodology to be used in applying CI's to the reliability analysis is continuing to be developed. Current guidance should be sought by contacting HDC.

## 8. Risk Analysis Using Capacity and Demand

This method of determining the dependability of equipment uses a statistical approach toward determining both the demands placed on the equipment and its ability to handle those demands. This method is an adaptation of the structural reliability assessment methods described in ETL 1110-2-532. In this procedure, limiting states of hydropower equipment performance are written as a factor of safety equal to the quotient of the capacity and demand. The variables describing this capacity and demand are considered random, and estimates of means and standard deviations are made based upon experience. Estimates of the mean and standard deviation of the factor of safety are then made using a Taylor Series Finite Difference procedure. The reliability index of the

equipment can then be estimated by approximating the distribution of factor of safety as log-normal. Mlaker (1993) and Mlaker and Bryant (1994) present technical details of this approach, along with an example. Their work is summarized in Appendix F.

## 9. Recommendations

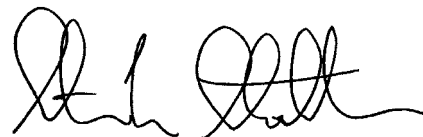
It is recommended that the procedures contained herein be used as guidance toward assessing the reliability of hydropower equipment. This ETL should be utilized in a team effort involving Operations, Engineering, Planning, Project Management, and the HDC to contribute to the evaluation of rehabilitation or upgrade alternatives.

## 10. Additional Information

Much of the work that is covered by this ETL is still under development. The latest information can be obtained from the HDC in Portland, OR, telephone (503) 808-4225. Also, worldwide web sites containing information relating to the hydroelectric power industry are listed in Appendix G.

FOR THE COMMANDER:

7 Appendices  
APP A - References  
APP B - Reliability Study Process  
APP C - Example Problem Description  
APP D - Hydroelectric Power Benefits Calculations  
APP E - Economic Models  
APP F - Review of Recent Research in Hydropower Reliability Analysis  
APP G - Worldwide Web Sites



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